

# Construction and Preliminary Application of the Variability $\rightarrow$ Luminosity Estimator

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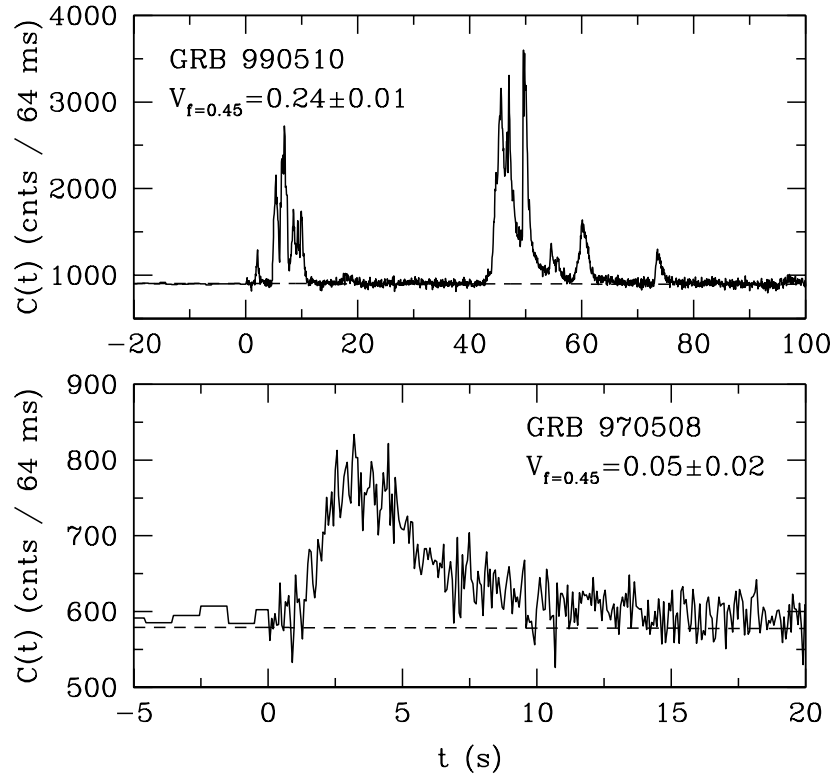
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**Abstract.** We present a possible Cepheid-like luminosity estimator for the long-duration gamma-ray bursts based on the variability of their light curves. We also present a preliminary application of this luminosity estimator to 907 long-duration bursts from the BATSE catalog.

## INTRODUCTION

Since gamma-ray bursts (GRBs) were first discovered [1], thousands of bursts have been detected by a wide variety of instruments, most notably, the Burst and Transient Source Experiment (BATSE) on the *Compton Gamma-Ray Observatory* (CGRO), which detected 2704 bursts by the end of CGRO's more than 9 year mission in 2000 June (see, e.g., [2]). However, the distance scale of the bursts remained uncertain until 1997, when BeppoSAX began localizing long-duration bursts to a few arcminutes on the sky, and distributing the locations to observers within hours of the bursts. This led to the discovery of X-ray [3], optical [4], and radio [5] afterglows, as well as host galaxies [6]. Subsequent observations led to the spectroscopic determination of burst redshifts, using absorption lines in the spectra of the afterglows (see, e.g., [7]), and emission lines in the spectra of the host galaxies (see, e.g., [8]). To date, redshifts have been measured for 13 bursts.

Recently, [9] (see also [10]), [11] (see also [12]), and [13] (see also [14]) have proposed trends between burst luminosity and quantities that can be measured directly from burst light curves, for the long-duration bursts. Using 1310 BATSE bursts for which peak fluxes and high resolution light curves were available, [9] have suggested that simple bursts (bursts dominated by a single, smooth pulse) are less luminous than complex bursts (bursts consisting of overlapping pulses); however, see [15]. Using a sample of 7 BATSE bursts for which spectroscopic redshifts, peak

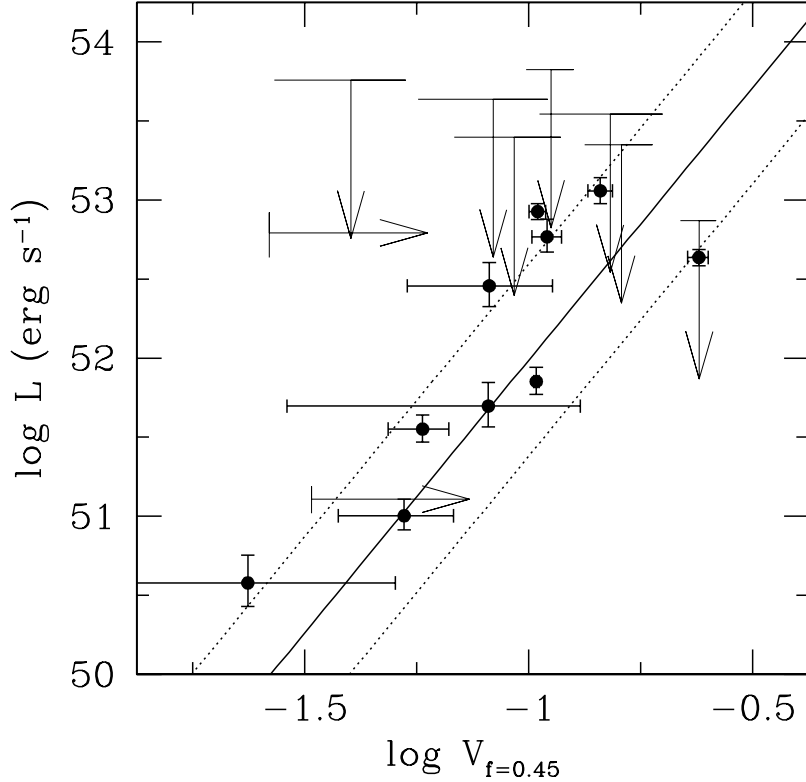


**FIGURE 1.** The  $> 25$  keV light curves of the most (GRB 990510) and least (GRB 970508) variable cosmological BATSE bursts in our sample. In the case of GRB 990510 ( $z = 1.619$ ), we find that  $V = 0.24 \pm 0.01$ . In the case of GRB 970508 ( $z = 0.835$ ), we find that  $V = 0.05 \pm 0.02$ .

fluxes, and high resolution light curves were available, [11] have suggested that more luminous bursts have shorter spectral lags (the interval of time between the peak of the light curve in different energy bands). Using the same 7 bursts, [13] have suggested that more luminous bursts have more variable light curves. These trends between luminosity and quantities that can be measured directly from light curves raise the exciting possibility that luminosities, and hence luminosity distances, might be inferred for the long-duration bursts from their light curves alone.

In this paper (see also [15,16]), we present a possible luminosity estimator for the long-duration bursts, the construction of which was motivated by the work of [14] and [13]. We term the luminosity estimator “Cepheid-like” in that it can be used to infer luminosities and luminosity distances for the long-duration bursts from the variabilities of their light curves alone. We also present a preliminary application of this luminosity estimator to 907 long-duration bursts from the BATSE catalog.

We discuss the construction of our measure  $V$  of the variability of a burst light curve §2. In §3, we discuss our expansion of the original [14] sample of 7 bursts to include a total of 20 bursts, including 13 BATSE bursts, 5 *Wind*/KONUS bursts,

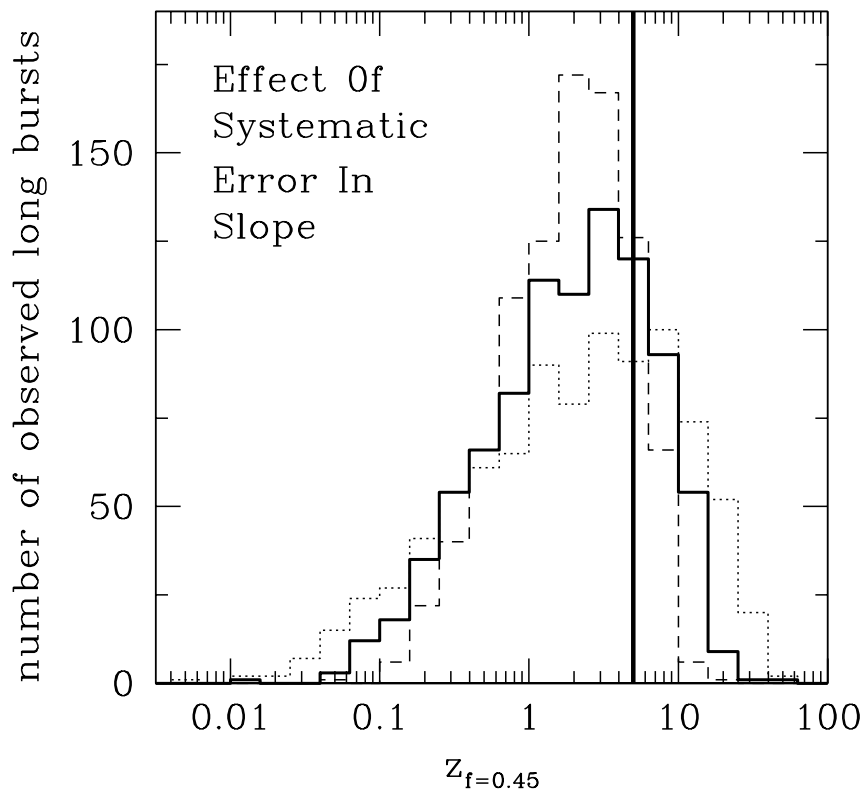


**FIGURE 2.** The variabilities  $V$  and isotropic-equivalent peak photon luminosities  $L$  between source-frame energies 100 and 1000 keV (see [15]) of the bursts in our sample, excluding GRB 980425. The solid and dotted lines mark the center and  $1\sigma$  widths of the best-fit model distribution of these bursts in the  $\log L$ - $\log V$  plane.

1 *Ulysses*/GRB burst, and 1 NEAR/XGRS burst. Also in §3, we discuss the construction of our luminosity estimator. We present our preliminary application of this luminosity estimator in §4.

## THE VARIABILITY MEASURE

Qualitatively,  $V$  is computed by taking the difference of the light curve and a smoothed version of the light curve, squaring this difference, summing the squared difference over time intervals, and appropriately normalizing the result. We rigorously construct  $V$  in [15]. We require it to have the following properties: (1) we define it in terms of physical, source-frame quantities, as opposed to measured, observer-frame quantities; (2) when converted to observer-frame quantities, all strong dependences on redshift and other difficult or impossible to measure quantities cancel out; (3) it is not biased by instrumental binning of the light curve,

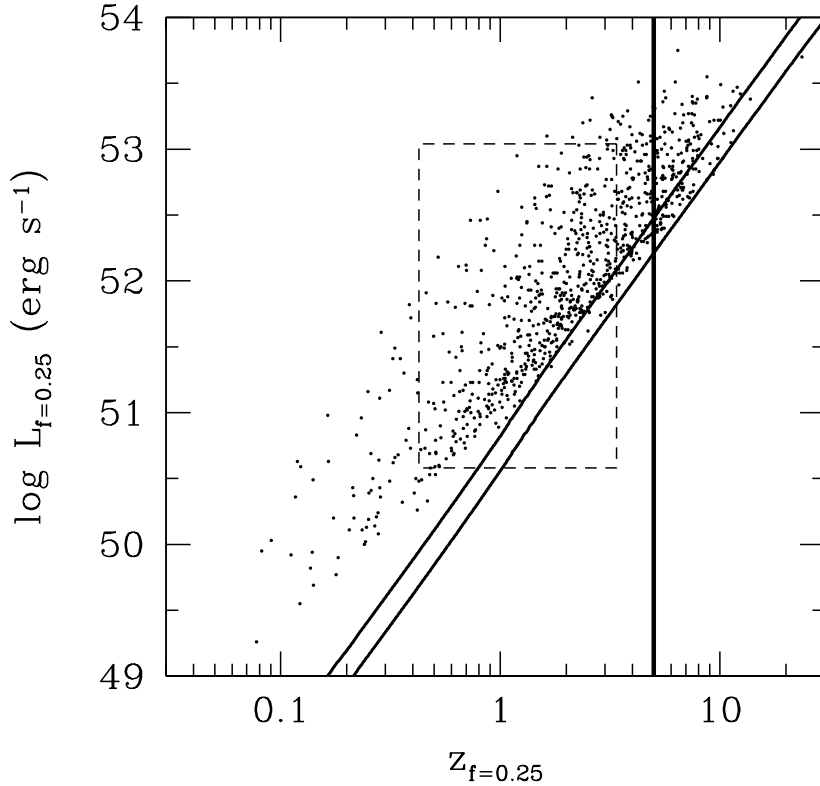


**FIGURE 3.** Solid histogram: The distribution of variability redshifts as determined using the best-fit luminosity estimator (Figure 2). Dotted and dashed histograms: The effect of varying the fitted slope of the luminosity estimator by  $\pm 1\sigma$  statistical uncertainty. The vertical line marks  $z = 5$ .

despite cosmological time dilation and the narrowing of the light curve’s temporal substructure at higher energies [17]; (4) it is not biased by Poisson noise, and consequently can be applied to faint bursts; and (5) it is robust; i.e., similar light curves always yield similar variabilities. Also in [15], we derive an expression for the statistical uncertainty in a light curve’s measured variability, and we describe how we combine variability measurements of light curves acquired in different energy bands into a single measurement of a burst’s variability. We plot the  $> 25$  keV light curves of the most and least variable cosmological BATSE bursts in our sample in Figure 1.

## THE LUMINOSITY ESTIMATOR

We list our sample of 20 bursts in Table 1 of [15]; it consists of every burst for which redshift information is currently available. Spectroscopic redshifts, peak fluxes, and high resolution light curves are available for 11 of these bursts; partial



**FIGURE 4.** The joint redshift and luminosity distribution of the qualitatively acceptable redshift distribution of Figure 3 (the dashed histogram). The solid curves mark the 90% and 10% detection thresholds of BATSE. The dashed box marks the redshift and luminosity ranges of the bursts that were used to construct the luminosity estimator, everything outside of this box is technically an extrapolation. The vertical line marks  $z = 5$ .

information is available for the remaining 9 bursts. We rigorously construct the luminosity estimator in [15], applying the Bayesian inference formalism developed by [18]. We plot the data and best-fit model of the distribution of these data in the  $\log L$ - $\log V$  plane in Figure 2.

## PRELIMINARY APPLICATION

We apply the best-fit luminosity estimator (Figure 2) to 1667 BATSE bursts, which are all of the BATSE bursts for which the necessary information was available as of the summer of 2000. To remove the short-duration bursts, we conservatively cut the bursts with durations of  $T_{90} < 10$  sec from the sample, reducing the number to 907. We plot the distribution of variability redshifts in Figure 3. A rigorous analysis of how statistical and systematic errors affect this distribution will be

presented elsewhere, but the largest effect is the statistical uncertainty in the fitted slope of the luminosity estimator. We plot how reasonable variations of this slope affect the distribution also in Figure 3. Although the original distribution has too many low- $z$  and high- $z$  bursts for comfort, reasonable variations appear to yield at least qualitatively acceptable distributions (see Figure 5 of [19]).

We plot the joint redshift and luminosity distribution of the qualitatively acceptable redshift distribution of Figure 3 (dashed histogram) in Figure 4. If systematic effects can be ruled out near BATSE's detection threshold, this distribution suggests that the luminosity distribution of the bursts is evolving, in which case no more than about 15% of bursts have redshifts greater than  $z = 5$ , in contrast to the results of [13] and [20].

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